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The Physics Case for an e^+e^- Super B-Factory

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Abstract

I share some personal reflections about the physics potential and the physics case that can be made for an e^+e^- high-luminosity B -meson factory, as presented in my summary talk at the recent *Super B-Factory Workshop* jointly organized by the BaBar and Belle Collaborations (Honolulu, Hawaii, January 2004). These brief remarks will appear as part of a forthcoming, comprehensive report on the physics potential of such a “ 10^{36} machine”.

1 Introductory remarks – Hopes and certainties

The physics potential of an e^+e^- super B -factory must be evaluated on the basis of a vision of the high-energy physics arena in the 2010s. By that time, the BaBar and Belle experiments will presumably have been completed, and each will have collected data samples in excess of 500 fb^{-1} . Hadronic B factories will have logged several years of data taking. There are excellent prospects that many parameters of the unitarity triangle will have been determined with great precision and in multiple ways. Likewise, many tests of the flavor sector and searches for New Physics will have been performed using a variety of rare B decays. A super B -factory operating at an e^+e^- collider with luminosity of order $\mathcal{L} \approx 10^{36}\text{ cm}^{-2}\text{ s}^{-1}$ would be the logical continuation of the B -factory program. If it is built, it will provide superb measurements of Standard Model parameters and perform a broad set of tests for New Physics. Such a facility could exhaust the potential of many measurements in the quark flavor sector, which could not be done otherwise.

However, it cannot be ignored that a super B -factory would come in the LHC era. By the time it could start operation, the LHC will most likely (hopefully ...) have discovered new particles, such as one or more Higgs bosons, SUSY partners of the Standard Model particles, Kaluza–Klein partners of the Standard Model particles, new fermions and gauge bosons of a dynamical electroweak symmetry-breaking sector, or whatever else will be revealed at the TeV scale. The crucial question is, therefore, whether a super B -factory has anything to contribute to the physics goals of our community in this era. More specifically, can it complement in a meaningful way the measurements that will be performed at the energy frontier? And while energy-frontier physics will most likely attract most attention in the next decade or two, can a super B -factory do fundamental measurements that could not be done elsewhere (including earlier B -factories)? Would it be indispensable to our community’s goal to comprehensively explore the physics at and beyond the TeV scale?

Fortunately, there exist indeed some big, open questions in flavor physics, to which we would love to find some answers. Let me mention three of them:

What is the dynamics of flavor? The gauge forces in the Standard Model do not distinguish between fermions belonging to different generations. All charged leptons have the same electrical charge. All quarks carry the same color charge. In almost all respects the fermions belonging to different generations are equal – but not quite, since their masses are different. Today, we understand very little about the underlying dynamics responsible for the phenomenon of generations. Why do generations exist? Why are there three of them? Why are the hierarchies of the fermion masses and mixing angles what they are? Why are these hierarchies different for quarks and leptons? We have good reasons to expect that the answers to these questions, if they can be found in the foreseeable future, will open the doors to some great discoveries (new symmetries, forces, dimensions, ...).

What is the origin of baryogenesis? The existential question about the origin of the matter–antimatter asymmetry provides a link between particle physics and the evolution of the Universe. The Standard Model satisfies the prerequisites for baryogenesis as spelled out in the Sakharov criteria: baryon-number violating processes are unsuppressed at high temperature;

CP-violating interactions are present due to complex couplings in the quark (and presumably, the lepton) sector; non-equilibrium processes can occur during phase transitions driven by the expansion of the Universe. However, quantitatively the observed matter abundance cannot be explained by the Standard Model (by many orders of magnitude). Additional contributions, either due to new CP-violating phases or new mechanisms of CP violation, are required.

Are there connections between flavor physics and TeV-scale physics? What can flavor physics tell us about the origin of electroweak symmetry breaking? And, if the world is supersymmetric at some high energy scale, what can flavor physics teach us about the mechanism of SUSY breaking? Whereas progress on the first two “flavor questions” is not guaranteed (though it would be most significant), we can hardly lose on this third question! Virtually any extension of the Standard Model that can solve the gauge hierarchy problem (i.e., the fact that the electroweak scale is so much lower than the GUT scale) naturally contains a plethora of new flavor parameters. Some prominent examples are:

- SUSY: hundreds of flavor- and/or CP-violating couplings, even in the MSSM and its next-to-minimal variants
- extra dimensions: flavor parameters of Kaluza–Klein states
- Technicolor: flavor couplings of Techni-fermions
- multi-Higgs models: CP-violating Higgs couplings
- Little Higgs models: flavor couplings of new gauge bosons (W' , Z') and fermions (t')

If New Physics exists at or below the TeV scale, its effects should show up (at some level of precision) in flavor physics. Flavor- and/or CP-violating interactions can only be studied using precision measurements at highest luminosity. Such studies would profit from the fact that the relevant mass scales will (hopefully) be known from the LHC.

To drive this last point home, let me recall some lessons from the past. Top quarks have been discovered through direct production at the Tevatron. In that way, their mass, spin, and color charge have been determined. Accurate predictions for the mass were available before, based on electroweak precision measurements at the Z pole, but also based on studies of B mesons. The rates for B – \bar{B} mixing, as well as for rare flavor-changing neutral current (FCNC) processes such as $B \rightarrow X_s \gamma$, are very sensitive to the value of the top-quark mass. More importantly, everything else we know about the top quark, such as its generation-changing couplings $|V_{ts}| \approx 0.040$ and $|V_{td}| \approx 0.008$, as well as its CP-violating interactions ($\arg(V_{td}) \approx -24^\circ$ with the standard choice of phase conventions), has come from studies of kaon and B physics. Next, recall the example of neutrino oscillations. The existence of neutrinos has been known for a long time, but it was the discovery of their flavor-changing interactions (neutrino oscillations) that has revolutionized our thinking about the lepton sector. We have learned that the hierarchy of the leptonic mixing matrix is very different from that in the quark sector, and we have discovered that leptogenesis and CP violation in the lepton sector may provide an alternative mechanism for baryogenesis.

In summary, exploring flavor aspects of the New Physics, whatever it may be, is not an exercise meant to fill the Particle Data Book. Rather, it is of crucial relevance to answer some fundamental, deep questions about Nature. Some questions for which we have a realistic chance of finding an answer with the help of a super B -factory are:

- Do non-standard CP phases exist? If so, this may provide new clues about baryogenesis.
- Is the electroweak symmetry-breaking sector flavor blind (minimal flavor violation)?
- Is the SUSY-breaking sector flavor blind?
- Do right-handed currents exist? This may provide clues about new gauge interactions and symmetries (left-right symmetry) at very high energy.

I will argue below that the interpretation of New Physics signals at a super B -factory can be tricky. But since it is our hope to answer some very profound questions, we must try as hard as we can.

The super B -factory workshops conducted in 2003 at SLAC and KEK have shown that a very strong physics case can be made for such a machine. During these workshops it has become evident (to me) that a strength of a super B -factory is precisely that its success will not depend on a single measurement – sometimes called a “killer application”. Several first-rate discoveries are possible and often likely. It is the breadth of possibilities and the reach of a super B -factory that make a compelling physics case. As with electroweak precision measurements, we can be sure that New Physics effects must show up at some level of precision in flavor physics. The question remains, at which level? In the “worst-case scenario” that we should not see any large signals in B physics, a super B -factory would play a similar role as LEP played for our strive toward the understanding of electroweak symmetry breaking. It would then impose severe constraints on model building for the post-LHC era.

2 CKM measurements – Sides and angles

At a super B -factory, the goal with regard to CKM measurements is simply stated: achieve what is theoretically possible! Many smart theoretical schemes have been invented during the past two decades for making “clean” measurements of CKM parameters. We can safely assume steady theoretical advances in our field (the past track record is impressive). This will lead to ever more clever amplitude methods, progress in heavy-quark expansions and effective field theories, and perhaps breakthroughs in lattice QCD. Unfortunately, all too often these theoretical proposals are limited by experimental realities. With a super B -factory, it would finally become possible to realize the full potential of these methods. One of the great assets of such a facility, which is particularly valuable in the context of precision CKM physics, is the availability of huge samples of super-clean events, for which the decay of the “other B meson” produced in $e^+e^- \rightarrow b\bar{b}$ at the $\Upsilon(4S)$ is tagged and fully reconstructed. Full reconstruction costs a factor 1000 or so in efficiency, which demands super B -factory luminosities. Once statistics is no longer of concern, the reduction in systematic error is a great benefit.

The sides $|V_{ub}|$ and $|V_{td}|$

A precision measurement of $|V_{ub}|$ with a theory error of 5% or less will require continued progress in theory. Determinations from exclusive semileptonic B decays need accurate predictions for $B \rightarrow$ light form factors from lattice QCD or effective field theory. Determinations from inclusive B decays need optimized cuts and dedicated studies of power corrections in the heavy-quark expansion. Recent advances using soft-collinear effective theory appear promising, but there is still much work left to be done. A super B -factory can provide vast, clean data samples of fully reconstructed decays, which would be an essential step toward eliminating the background from semileptonic decays with charm hadrons in the final state. It can also yield high-precision data on the q^2 dependence of form factors, and on the $B \rightarrow X_s \gamma$ photon spectrum down to $E_\gamma \sim 1.8$ GeV or lower. This would provide important constraints on theory parameters (e.g., shape functions).

Another road toward measuring $|V_{ub}|$ is to study the leptonic decays $B \rightarrow \mu\nu$ or $B \rightarrow \tau\nu$, which would be accessible at a Super B -factory. The rates for these processes are proportional to $f_B^2 |V_{ub}|^2$. A lattice prediction for the B -meson decay constant can then be used to obtain $|V_{ub}|$. Alternatively, one can combine a measurement of the leptonic rate with that for the $B-\bar{B}$ mixing frequency to obtain the ratio $B_B^{-1/2} |V_{ub}/V_{td}|$, where the hadronic B_B parameter would again have to be provided by lattice QCD. Such a determination would impose an interesting constraint on the parameters of the unitarity triangle.

A precision measurement of $|V_{td}|$ itself would require continued progress in lattice QCD. Rare radiative decays (or rare kaon decays) could also help to further improve our knowledge of this parameter.

The angles $\beta = \phi_1$ and $\gamma = \phi_3$

A super B -factory would allow us to exploit the full theory potential of various methods for model-independent extractions of CP phases. We could finally do the measurements whose analyses require the least amount of theory input. In the Standard Model, it's really all about γ (the unique CP phase in B decays), in various combinations with β (the CP phase in $B-\bar{B}$ mixing). The importance of pursuing γ measurements using different strategies (conventionally called measurements of α and γ) is that “ γ measurements” measure γ in pure tree processes, whereas “ α measurements” probe γ in processes where penguins are present. Comparing the results obtained using these different methods probes for New Physics in penguin transitions, which are prominent examples of loop-induced FCNC processes in the Standard Model. The precision that can be reached on β and γ using various techniques accessible at a super B -factory is most impressive. A lot of marvelous physics can be done once such measurements will be at hand.

3 Searching for New Physics – Never stop exploring

Probing New Physics with CKM measurements

The path is clear. If different determinations of unitarity-triangle parameters would turn out to be inconsistent, then this would signal the presence of some New Physics. For instance, it is interesting to confront the “standard analysis” of the unitarity triangle, which is primarily sensitive to New Physics in B – \bar{B} and K – \bar{K} mixing, with mixing-independent constructions using charmless hadronic decays such as $B \rightarrow \pi K$, $B \rightarrow \pi\pi$, $B \rightarrow \pi\rho$, and others. These studies, while not independent of theory, have already established CP violation in the bottom sector of the CKM matrix (the fact that $\text{Im}(V_{ub}) \neq 0$ with the standard choice of phase conventions), while still leaving ample room for possible New Physics effects in $b \rightarrow s$ FCNC processes. (Some authors have argued that there are already some tantalizing hints of New Physics in $b \rightarrow s$ transitions sensitive to “electroweak penguin”-type interactions.)

It is also interesting to confront different determinations of β with each other, such as the measurement of $\sin 2\beta$ from processes based on $b \rightarrow s\bar{c}c$ vs. $b \rightarrow s\bar{s}s$ or $b \rightarrow s\bar{q}q$ (with $q = u, d$) quark-level transitions. One of the burning issues today is whether there is something real to the “ ϕK_s anomaly” seen by Belle, but not confirmed by BaBar. With more precise data, many other decay modes can be added to obtain interesting information and perform non-trivial tests of the Standard Model.

Yet, let me stress that many more tests for New Physics can be done outside the realm of CKM measurements. Several of those involve rare hadronic B decays. Others make use of inclusive decay processes. The general strategy is to look for niches where the “Standard Model background” is small or absent. One cannot overemphasize the importance of such “null (or close-to-null) measurements”, as they provide direct windows to physics beyond the Standard Model. In comparison, the search for New Physics in CKM measurements always suffers from a large Standard Model background.

Probing New Physics in exclusive decays

Rare (charmless) hadronic B decays are usually characterized by the presence of several competing decay mechanisms, often classified in terms of flavor topologies (trees, penguins, electroweak penguins, annihilation graphs, exchange graphs). These refer to the flow of flavor lines in a graph but do *not* indicate the possibility of multiple gluon exchanges. Therefore, reality is far more complicated. Until a few years ago, such nonleptonic decay processes were believed to be intractable theoretically. This has changed recently, thanks to the advent of QCD factorization theorems, perturbative QCD methods, and soft-collinear effective theory, which complement previous approaches based on flavor symmetries. Together, these approaches build the foundation of a systematic heavy-quark expansion for exclusive B decays, much like heavy-quark effective theory provided the basis for such an expansion in the (much simpler) case of exclusive $B \rightarrow D^{(*)}l\nu$ decays. (The dispute between QCD factorization and pQCD practitioners is also beginning to be resolved, since the issue of Sudakov logarithms in heavy-to-light transition amplitudes is now under good theoretical control.)

With ever improving theoretical control over exclusive B decay processes, several possibilities for tests for New Physics become accessible. A partial list includes the measurement

of $\sin 2\beta$ from the time-dependent CP asymmetry in $B \rightarrow \phi K_s$ decays, probing electroweak penguins in rate measurements using $B \rightarrow \pi K_s$ decays, and searching for New Physics by measuring CP asymmetries in $B \rightarrow K^* \gamma$ decays and the forward-backward asymmetry in $B \rightarrow Kl^+l^-$ decays. While there will always be an element of theory uncertainty left in these analyses, in the cases above these uncertainties can be controlled with rather good precision, so that large deviations from Standard Model predictions would have to be interpreted as signs of New Physics. (Indeed, some intriguing “hints of anomalies” are seen in present data.)

Probing New Physics in inclusive decays

This is the more traditional approach, which profits from the availability of reliable theoretical calculations. Several methods have been discussed over the years, including precision measurements of the $B \rightarrow X_s \gamma$ branching ratio and CP asymmetry, the $B \rightarrow X_s l^+l^-$ rate and forward-backward asymmetry, the inclusive $B \rightarrow X_s \nu\bar{\nu}$ decay rate, and some of the above with X_s replaced with X_d . The mode $B \rightarrow X_s \nu\bar{\nu}$ is tough. This would definitely be super B -factory territory.

4 Interpreting New Physics – The quest to measure non-standard flavor parameters

The primary goal of a super B -factory would be to measure New Physics parameters in the flavor sector. In general, non-standard contributions to flavor-changing processes can be parametrized in terms of the magnitudes and CP-violating phases of the Wilson coefficients in a low-energy effective weak Hamiltonian. The main obstacle is that, in general, there can be many such coefficients! Ideally, we would like to probe and measure these couplings in a selective, surgical way, thereby measuring the fundamental coupling parameters of new particles. Equally important is to study the *patterns* of the New Physics, which may reveal important clues about flavor dynamics at very high (beyond-LHC) energy scales.

CKM measurements

A clean interpretation of New Physics signals in CKM measurements is difficult (if at all possible) due to the large Standard Model background. An important message is this: In the presence of New Physics, methods that are “clean” (i.e., that do not rely on theory input) in the Standard Model in general become sensitive to hadronic uncertainties. This point is sometimes overlooked. Consider, as an example, the Gronau–London method for measuring γ (or α) from $B \rightarrow \pi\pi$ decays. In the Standard Model, one needs five measurements in order to extract the four unknown hadronic parameters $|P/T|$, $|C/T|$, $\delta_{P/T}$, $\delta_{C/T}$ along with γ . With New Physics present, there are six additional amplitude parameters and not enough observables to fix them. But things are, in fact, worse than that, for the six new parameters are linear combinations of New Physics parameters and a large number of hadronic parameters – the amplitudes and strong phases of the many $B \rightarrow \pi\pi$ matrix elements of the operators in

the effective weak Hamiltonian. (It is a misconception to think that there is only one strong phase each for the $\pi\pi$ final states with isospin $I = 0$ or 2 .)

The problem is, simply put, that CKM physics is hard. Consider how difficult it has been (and still is) to determine the four parameters of the CKM matrix, *for which there is no background*, since the CKM matrix is the only source of flavor violation in the Standard Model. With New Physics present, the Standard Model is a source of irreducible background for measurements in the flavor sector. In most cases, the subtraction of this background introduces large hadronic uncertainties.

Non-CKM measurements

In some cases, the Standard Model background can be strongly reduced or even eliminated, so that one can directly probe certain types of New Physics operators. Examples are decay observables sensitive to electroweak penguins, such as rate and CP asymmetry measurements in $B \rightarrow \phi K_s$ and $B \rightarrow \pi K_s$ decays. The idea is to look for certain patterns of “isospin violation”, which in the Standard Model are highly suppressed, because they only arise at second order in electroweak interactions (“electroweak penguins”). This fact offers a window for seeing New Physics effects with little Standard Model background. In many models, New Physics can fake the signature of electroweak penguin operators *without* an additional electroweak coupling involved (“trojan penguins”). This provides sensitivity to sometimes very large energy scales (up to several TeV). In other cases, such as $B \rightarrow VV$ modes or $B \rightarrow K^*\gamma$ decay, one can probe specific operators with non-standard chirality, thereby eliminating the Standard Model background altogether.

Searches for New Physics in inclusive decays are often simpler to interpret, as they are afflicted by smaller theoretical uncertainties in the relation between observables and Wilson coefficient functions. Still, in general it can be difficult to disentangle the contributions from (potentially many) new Wilson coefficients, as only a limited number of observables can be measured experimentally.

Importance of patterns of New Physics

Let me close this discussion on an optimistic note. Even if it is hard to cleanly disentangle the contributions from different New Physics operators, CKM measurements will play an important role in helping to distinguish between different *classes* of New Physics effects, such as New Physics in mixing vs. New Physics in decay amplitudes, or New Physics in $b \rightarrow s$ vs. $b \rightarrow d$ FCNC transitions. CKM measurements might indicate the existence of new CP-violating interactions or new flavor-changing interactions not present in the Standard Model. Also, they will help to differentiate between models with and without minimal flavor violation.

Studies of exclusive hadronic decays can help to distinguish between the “flavor-blind” transitions $b \rightarrow sg$ and $b \rightarrow s(\bar{q}q)_{\text{singlet}}$ and “flavor-specific” $b \rightarrow s(\bar{q}q)_{\text{non-singlet}}$ decays. We will also be in a position to check for the existence of right-handed currents and, more generally, probe for operators with non-standard chirality.

5 Conclusion

Precisely because we don't know what to expect and what to look for, it is the breadth of the physics program at a super B -factory that will guarantee success. The discovery of new particles at the LHC would help to interpret the possible findings of non-standard signals and guide further studies. Even finding no effects in some channels would provide important clues. Based on these considerations, it is my conviction that the physics case for a super B -factory is compelling. Such a facility would be an obvious choice to pursue if any of the “anomalies” seen in the present B -factory data would ultimately turn out to be real effects of New Physics.

Disclaimer

Above I have present some personal reflections about the physics potential and the physics case that can be made for a high-luminosity e^+e^- B -factory. My thinking about such a facility has evolved over a period of several years, starting with a workshop in June 2000 in Glen Arbor, Lake Michigan that I helped organize. During this process, I have profited from numerous discussions with colleagues. I have also been influenced significantly by the splendid performance of the SLAC and KEK B -factories and of the BaBar and Belle experiments. Many things that were nearly unthinkable even a few years ago now appear within reach. (It is characteristic that the title of our 2000 Workshop referred to a 10^{34} machine. In other words, the luminosity target has gone up by a factor 10 every two years!)

I have kept these introductory remarks brief. Much of the supporting material will be presented in a forthcoming, comprehensive report on the physics potential of a “ 10^{36} machine”.

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